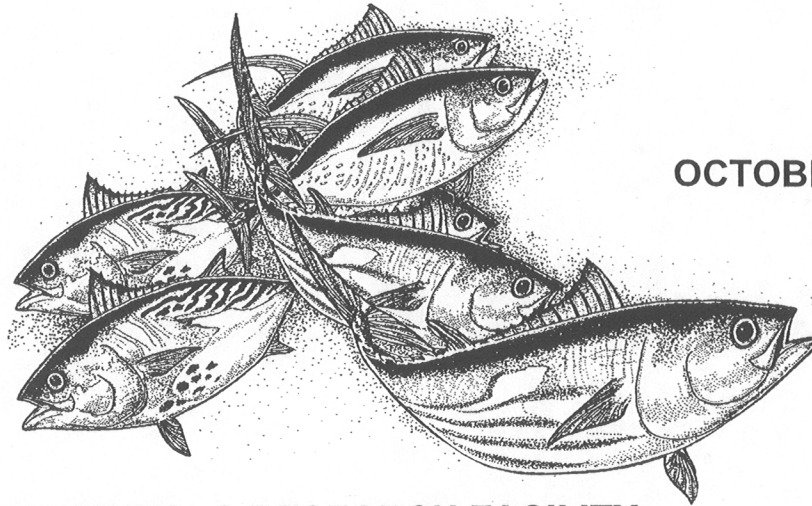


NOAA Technical Memorandum NMFS



OCTOBER 1999

THE KEWALO RESEARCH FACILITY: ON THE FOREFRONT FOR MORE THAN 40 YEARS

Compiled and Edited by

Richard W. Brill

NOAA-TM-NMFS-SWFSC-281

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
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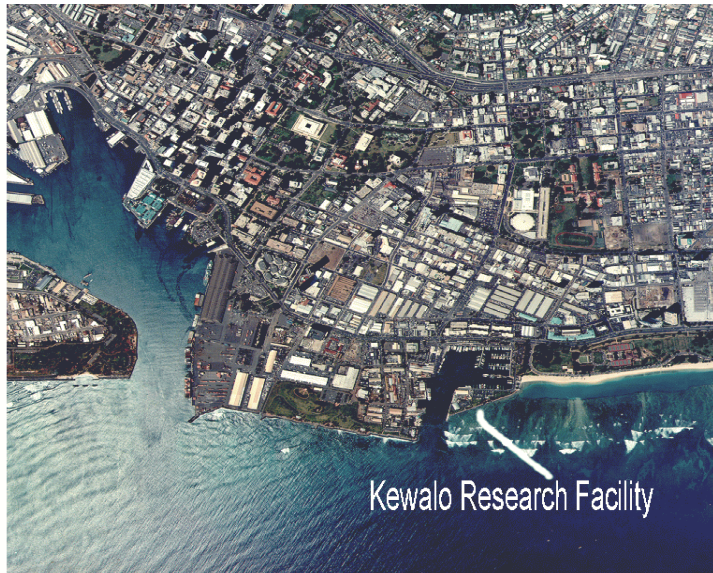
The National Oceanic and Atmospheric Administration (NOAA), organized in 1970, has evolved into an agency which establishes national policies and manages and conserves our oceanic, coastal, and atmospheric resources. An organizational element within NOAA, the Office of Fisheries is responsible for fisheries policy and the direction of the National Marine Fisheries Service (NMFS).

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THE KEWALO RESEARCH FACILITY

FORWARD

K*ewalo* can be translated from the Hawaiian as "the place of wailing." Historical descriptions of the area called Kewalo on the Island of Oahu give meaning to the translation. In ancient times this section of land contained a spring which, before the Hawaiian Islands conversion to Christianity, was used as a place for human sacrifices. Here *kauwa* (outcasts) were first drowned before being taken to the *Heiau of Kanelaau* (temple) on the slopes of Punchbowl Crater for burning in the *imu ahi* (fire oven). Kewalo Basin, as part of the modern city of Honolulu is, of course, no longer used for such purposes. Today it is the home of many commercial and recreational fishing boats, tour boats, a fresh fish auction house, and other marine related enterprises. Kewalo Basin is also the site of the National Marine Fisheries Service's renowned **Kewalo Research Facility**.



An aerial view of the southern coast of the Island of Oahu (city of Honolulu); Punchbowl Memorial Cemetery is at the top center, Kewalo Basin at the bottom center. The financial district in downtown Honolulu is immediately behind Honolulu Harbor (lower left).

The **Kewalo Research Facility** is able to obtain and maintain tuna in captivity because of several conditions unique to its site. Commercial live bait tuna fishing boats dock in Kewalo Basin, literally at the laboratory's front door. Also, because the facility was built over a filled-in coral reef, and Hawaii's mild climate, saltwater wells are able to provide clean seawater at temperatures appropriate for holding tunas the year round.

The area occupied by the **Kewalo Research Facility** was once a shallow submerged coral reef. In 1945 the U.S. Navy dredged a small harbor which became known as Kewalo Basin. Dredge spoils and sanitary fill was dumped on the adjacent coral reef to create protecting land areas. The harbor was later turned over to the Territory of Hawaii and was subsequently enlarged. In July 1958, the Honolulu Laboratory of the National Marine Fisheries Service, then a part of the Fish and Wildlife Service, negotiated a lease to the grounds and building on the spit of artificial land at the southeast entrance of Kewalo Basin and established the **Kewalo Research Facility**.

The facility has a low profile and goes unnoticed by the many tourists, surfers, and fishermen that frequent the area. But within the 0.4 hectare (0.98 acre) area is a truly remarkable research laboratory. The main building houses offices, laboratories tailored for various research activities, a machine shop, and storage areas. Two saltwater wells on the adjoining grounds have the capacity to produce high quality coral filtered seawater at a rate of over 48,000 gallons (181,700

liters) per hour. The seawater is pumped to aerators to be oxygenated and then distributed to various tanks including a series of three 20,000-gallon (75,706-liter) circular pools and 200,000-gal (757,060-liter) oceanarium specifically designed for holding tunas, three 10,000-gal (37,854-liter) tanks specifically designed for Hawaiian monk seals, and specially designed experimental tanks of various sizes.

At its inception, the **Kewalo Research Facility** was the only research center in the world able to maintain live tunas in captivity throughout the year for use in behavioral and physiological research. Although today several additional laboratories and aquaria also routinely maintain tunas in captivity for display and research, the **Kewalo Research Facility's** international reputation continues to attract established scientists of diverse backgrounds and expertise to this unique laboratory where experiments requiring access to live tunas and other marine animals can be conducted. Indeed, the uniqueness of the **Kewalo Research Facility** and the past almost 40 years of quality research have engendered it an enviable international reputation.

Yellowfin tuna being held at the **Kewalo Research Facility**.



In the important commercial tuna fisheries of the world, prediction of the distribution and abundance of the various tunas species that comprise the resource is a major biological problem. Analyses of environmental data have provided correlations between tuna distribution and various oceanographic and meteorological conditions, but the mechanisms that determine the distribution, availability, and migrations of tunas are not completely known. Temperature, oxygen, and food availability all seem to influence tuna movements and to limit their vertical and horizontal distributions. The **Kewalo Research Facility** is the center for ongoing research programs designed to examine the effects of the most important environmental parameters on the behavior and physiology of tunas. These programs will ultimately allow fishermen, fisheries scientists, and fisheries managers to predict how environmental factors affect the distribution, vulnerability to specific fishing gears, and movements of tunas; and ultimately to better manage and conserve this important resource.



Hawaiian-style live-bait tuna fishing boat (above). These types of vessels have been catching for skipjack and yellowfin tunas near the main Hawaiian Islands since the 1930's. A local inshore anchovy (*Stolephorus purpureus*) is netted from bays and used as live bait to create a feeding frenzy behind the boat. The fish to strike feathered jigs with barbless hooks (below)



Live tunas delivered to the **Kewalo Research Facility** are purchased from local live bait tuna fishing boats. Fish are placed in the bait wells for the trip back to Kewalo Basin.

Upon arrival, fish are moved into a fiberglass transfer tank, a crane is used to place the transfer tank into one of the (8 m diameter, 1.5 m deep) holding tanks, then tipped allowing the fish to swim out. This technique, which has evolved over the years, minimizes handling of the fish and the resultant skin and fin damage.



Hawaiian monk seal and green sea turtle at the **Kewalo Research Facility**

In recent years the role of the **Kewalo Research Facility** has, however, expanded. It now serves the research needs of scientists charged with the responsibility of enhancing the survival of threatened and endangered species, such as the Hawaiian monk seal (*Monachus schauinslandi*) and green turtle (*Chelonia mydas*).

RESEARCH ACTIVITIES -- The early years

Tuna stocks are distributed throughout the world's oceans and form an important economic resource for many countries. The value of worldwide tuna catches is currently estimated at close to **\$4 Billion/year**. The United States alone processes over 600 million pounds of canned tuna per annum, valued at approximately \$1 billion. Despite the high economic value of tuna stocks, very little research had been done with live specimens before 1958, because no facility existed to maintain tunas in captivity. The initial goals of the **Kewalo Research Facility** were, therefore, to develop a program to maintain live tunas in captivity as experimental animals. Because this was truly a pioneering effort, research was aimed at collecting data that would serve as the foundation for future investigations. This early work uncovered these interesting facts about tunas:

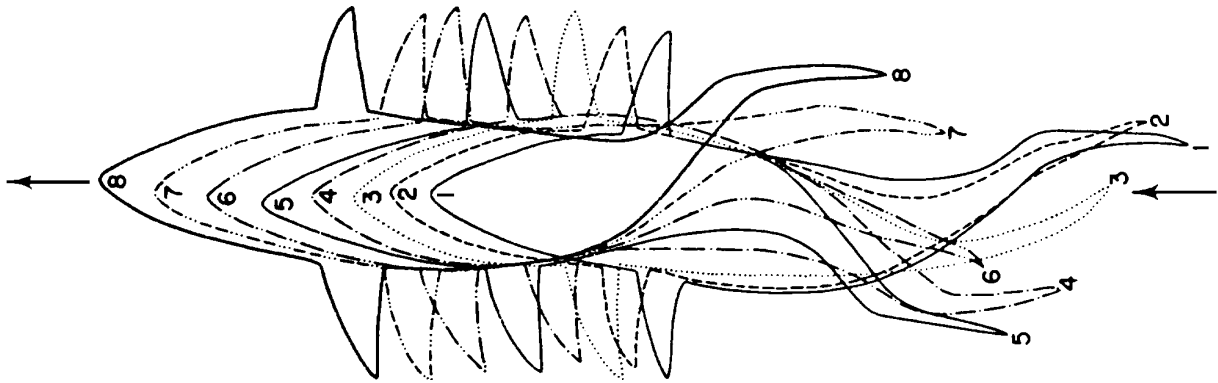
Tunas are heavier than water and must continuously swim to keep from sinking.

Tunas breathe by simply opening their mouths so that water is forced over their gills as they swim; they sink and suffocate if they stop swimming.

Minimum swimming speeds of tunas are dependent upon the lifting area of fins and the density of the fish, and are not a function of either respiratory requirements or the search for food.

All tunas have the following adaptations for continuous swimming: (1) a high hemoglobin level in the blood to carry sufficient oxygen to maintain continuous muscle activity; (2) a large proportion of the muscle made up of red muscle fibers that are specialized, like muscles of the heart, for continuous activity; and (3) a streamlined body shape to reduce hydrodynamic drag.

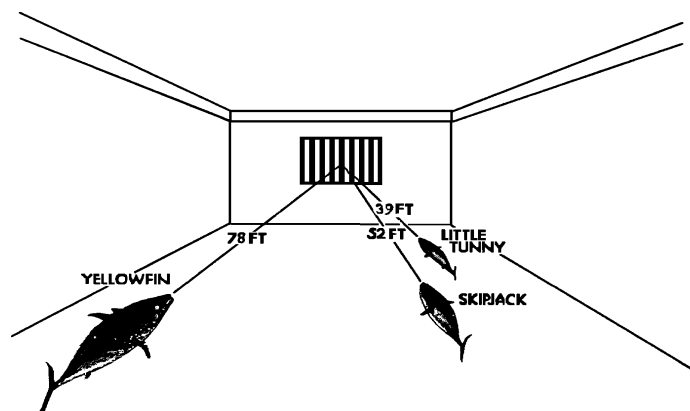
Larger species of tunas have evolved two morphological features to reduce the energy required to keep from sinking: (1) pectoral fins became larger to produce more lift; and (2) gas bladders developed to decrease density. [Although gas bladders are very effective in reducing the density of fish, they limit the vertical movements of tunas. A fast vertical ascent to the surface can cause large changes in volume and, in the extreme, burst the gas bladder. Small species of tunas, such as skipjack tuna (*Katsuwonus pelamis*), do not have gas bladders.]



The **Kewalo Research Facility** made it possible to closely observe captive fish and produce the first high-speed movies of swimming tuna. The analysis of the film provided intimate details of swimming speed, tail beat rates, body postures and flexures, and how the changing positions of fins and finlets possibly reduce drag. The line drawing shown here was traced from successive cine frames (camera speed 100 frames per second) for one complete caudal fin beat cycle of a kawakawa. The swimming speed of this fish was 8.2 body lengths per second which was produced by a tail beat frequency of 14.3 tail beats per second.

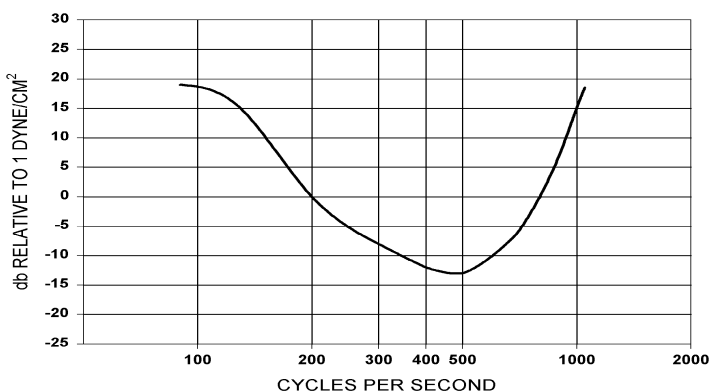
Other early experiments were designed to determine the sensory abilities of tunas -- how well they smell, taste, hear, see, and sense changes in water temperature. The rationale for these studies was that a basic understanding of the sensory capabilities of tunas would be useful in the design of fishing gear and new fishing methods, and in locating tunas.

To determine how well tunas can see, studies were conducted on their visual acuity (the ability to see the fine details of objects). Of the three species tested, it was determined that yellowfin tuna (*Thunnus albacares*) could see better than skipjack tuna, and the latter better than kawakawa (*Euthynnus affinis*). Further experiments on the optical system of restrained tuna showed that they are color-blind and are most sensitive to blue light.



To measure tuna's reaction to various sensory stimuli, an observer must be able to detect the fish's response to these stimuli. It was found that tunas can be trained to perform a specific act in response to stimuli if they are rewarded. To measure how well they can see, tunas were trained to respond differently to vertical and horizontal bars that were projected onto an underwater screen by giving rewards (food) or punishment (mild electric shock). These experiments showed that at a constant brightness, a yellowfin tuna sees details of an object better than a skipjack tuna, and a skipjack tuna better than a kawakawa.

Experiments to define the hearing ability of tunas made it possible to construct a hearing curve for a tuna, the first ever for a scombrid, and to determine their auditory thresholds (the lowest level of sound that can be heard at a specific frequency). It was determined that the hearing range of yellowfin tuna is from about 200 to 2,000 Hz (cycles per second), and that their hearing is most acute at 500 Hz.



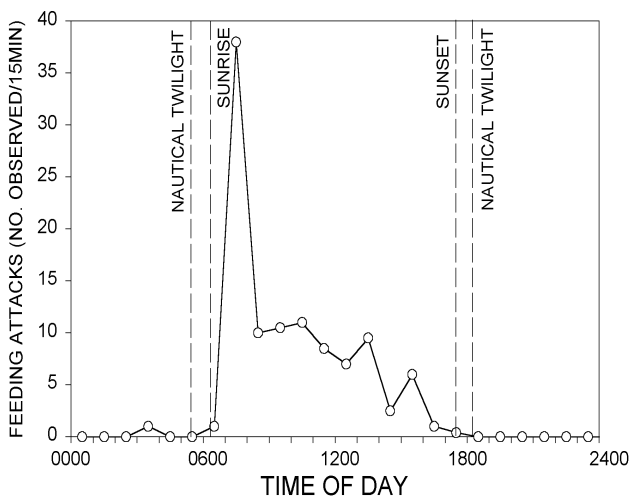
Experiments to determine the hearing ability of tunas were conducted in a pool specially constructed to insulate the fish from outside sounds. The test fish were first trained to recognize a pure "white" sound and then to react to the sound stimulus by swimming through a maze for a reward. The yellowfin tuna best hears sounds that are near 500 Hz as shown by the dip at that frequency in the hearing curve. Sounds near this frequency are common in the ocean, as for example, the sound produced by the swimming of a school of small fish.

Experiments at the **Kewalo Research Facility** also showed that tunas have a highly developed sense of smell. A strong response was elicited from a school of kawakawa when a liter (1.06 quarts) of water in which a small fish (a smelt weighing 10 g or 0.4 ounce) had been dipped for 10 seconds was introduced to their holding tank. The response was elicited even though the rinse water was further diluted by its introduction through the inflow seawater system! A study of the morphological structure of the nares (nose) of the tunas revealed that they can "sniff" the water. Each jaw movement of a tuna produces a pumping action that forces water past their nasal rosettes (odor receptors). Observations of fish in captivity showed this pumping action to be continuous.

Two other research projects were designed to determine tunas' ability to perceive changes in water temperature. One experiment made use of the observation that the heart rate of a restrained tuna slows when the fish is presented with an external stimulus, such as a change in water temperature. In the second experiment a free swimming fish was rewarded with food each time

it was able to recognize a temperature difference when cooler or warmer water was added to the tank. In restrained fish, a temperature change of 1 C elicited a response. Free swimming fish were able to do even better, they showed that they could perceive a temperature difference of as little as 0.1 C.

Early work on the feeding and digestion rates of tunas showed that these fish can digest a meal several times faster than other fish species. Prey organisms are not homogeneously distributed in the open ocean, but are found in patchy concentrations in space and time. Tunas therefore exist in a "feast or famine" situation and must eat whenever they find food. Knowledge of digestion and feeding rates of fishes adapted to such environments is important for understanding the of growth and worldwide distribution of tunas and can be of practical value to commercial fishermen.



The changes in the feeding activity of kawakawa (*Euthynnus affinis*) during a 24-hour period as shown in this graph is typical for tunas. When fish in captivity were provided with a constant supply of food, feeding motivation was highest at early morning, followed by a rapid decrease through noon, and two smaller peaks at mid-afternoon. Fish did not feed at night. This behavior is consistent with the rapid digestion of tunas which is from two to five times faster than that of other fishes. When fed continuously, tunas can consume up to of 15% of body weight per day. The drive to attack prey is dependent on the amount of food in the stomach. Intense feeding always occurs in the morning when the stomach is empty; feeding slows when the stomach is 80% filled.

As techniques for capture, transport, and maintenance of tunas improved, the number of live tunas available for experimental purposes increased proportionately. This made it possible to increase the variety of behavioral and physiological studies conducted at the **Kewalo Research Facility**.

RESEARCH ACTIVITIES -- The later years

Tunas

Thermoregulation -- Studies at the **Kewalo Research Facility** confirmed that tunas have a remarkable ability to maintain body temperatures higher than the water in which they are swimming. This ability is attributable to vascular counter-current heat exchangers that retain the heat produced by metabolic activity within the muscles. In other fishes, metabolic heat is lost into the surrounding water via the gills and body surface. As a predator, the ability to maintain an elevated body temperature probably gives tunas an advantage over other fishes

because it allows them to operate at higher activity levels. Depending on the activity and size of the fish, muscle temperatures of tunas can range from 2° to 21° C above ambient temperature. The accumulation of knowledge on the effects of temperature on tuna physiology allowed work on more sophisticated experiments, such as those designed to determine whether tunas can physiologically or behaviorally thermoregulate. The first evidence of physiological thermoregulation in tunas was obtained in experiments with yellowfin tuna. Fish, placed in a doughnut-shaped tank, were shown to be able to alter their rates of heat loss independently of swimming speed (that is physiologically thermoregulate) as the water temperature was changed at 12-hour intervals. This ability to physiologically thermoregulate, however, has not yet been demonstrated in all species of tuna.

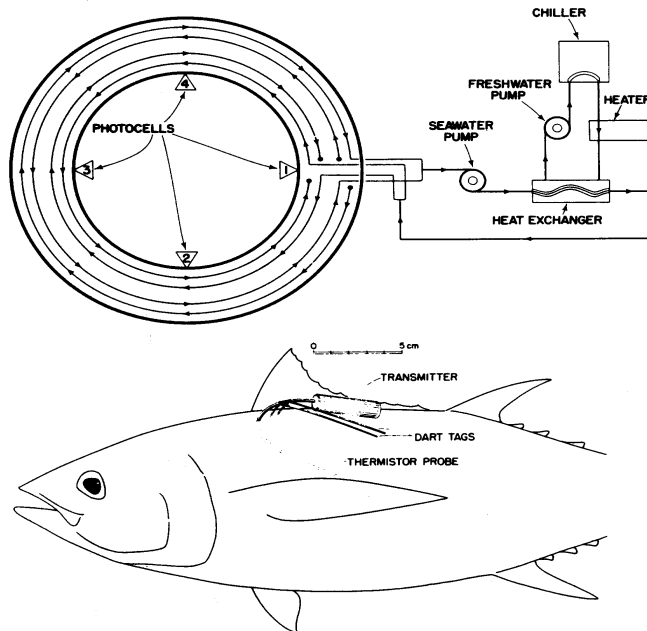


Figure 9. Schematic diagram of the annular test tank and temperature control system used to measure the physiological thermoregulatory ability of skipjack and yellowfin tunas. Seawater was delivered to and removed from the swimming channel through a series of perforated pipes on the bottom of the tank. A computer was used to continually calculate the fish's swimming speed based on data coming from the four photocells that monitored the fish's position in the swimming channel. Deep red muscle temperature was measured by a thermistor probe connected to an ultrasonic transmitter. In this way, muscle temperature could be monitored in free-swimming fish. Water temperature is controlled within 0.05°C.

Energetics -- Tuna metabolic rates present interesting paradoxes. Tunas have a higher energy demands than other fishes yet they inhabit a very food-poor environment: the tropical oceans. How do tunas obtain the energy they need when they live in a virtual desert? Anyone seeing the sleek, streamlined shape of a swimming tuna is impressed with its design. Each of five swimming fins can be withdrawn into a slot or recess, leaving the body surface perfectly smooth. Despite their hydrodynamically shaped bodies, tunas require more energy to swim at their cruising speed than do other fishes swimming at the same speeds. Shouldn't tunas be more efficient?

The measurement of tuna metabolic rates has a long history at the **Kewalo Research Facility**. Past projects included measurement of standard metabolic rate (metabolic rate at zero activity), and studies of the effects of size, temperature, and speed on active metabolic rate. Later work

was designed to re-examine earlier results, which were based on oxygen consumption (respirometry), by directly measuring changes in whole fish energy content (calorimetry).

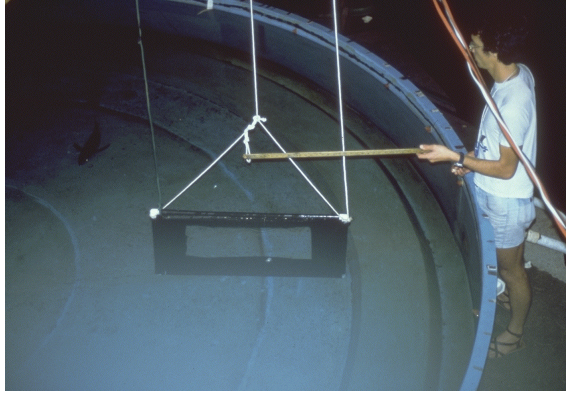
Answers to the paradox of high metabolic rates may come from the advantages a high metabolic rate provides with respect to agility and mobility in hunting and capturing prey. The data from these studies indicated that tunas become more efficient than other fishes at higher swimming speeds. For tunas, high metabolic rates at low activities appear to be a physiological necessity for greater efficiency at high swimming speeds during feeding or when escaping from predators. And the unique ability of tunas to conserve metabolic heat may also turn high metabolic rates to advantage by keeping the tuna's swimming muscles warm when they penetrate cold, deep water in pursuit of prey.

Geomagnetic Sensitivity -- Tunas are among the most highly migratory fishes. They routinely make transoceanic migrations but also show the ability to precisely navigate on a daily basis. An understanding of the mechanism guiding the movements and long distance migrations of tunas is therefore central to understanding the biology of these species.

Since migration represents a substantial investment of energy, there has probably been intense evolutionary pressure to develop accurate sensory systems capable of guiding these movements. However, no special abilities useful in navigation had been detected among the common previously recognized sensory systems (vision, smell, taste, etc.) of tunas. Yet there was one other possibility, that tunas possessed a magnetic compass sense.

After the discovery that yellowfin tuna have up to 10 million crystals of magnetite (a biologically generated magnetic crystal) in the ethmoid bones of the skull, and that the fish produce the magnetite under very closely controlled conditions of size, shape, and chemical composition, studies were undertaken to test the ability of yellowfin tuna to discriminate between different magnetic fields. The fish were trained to perform a conditioned response (swimming through a hoop) at a consistent rate. They were then tested by rewarding them with food when one magnetic field was present in the tank and by punishment (withholding food) when the second field was present. If the fish were able to detect the difference between the two magnetic fields, maintaining a high rate of response during positively reinforced trials would maximize food rewards, whereas a low rate of response during negatively reinforced trials would minimize the cost of responding. Thus, discrimination would be measured as a difference in the rates at which the fish swim through the hoop in anticipation of positive or negative reinforcement. These experiments were clearly able to show that yellowfin tuna can learn to use magnetic field information to make appropriate decisions; the first proof tunas possess a magnetic sense which is probably could be used for navigation.

Related studies showed that a large branch of the anterior lateral line nerve ramifies in the area of the ethmoid bones which contain the magnetite crystals. It is therefore possible that a branch of this nerve may be associated with the magnetite crystals and form the magnetoreceptor organ, although this still remains to be determined.



A yellowfin tuna being trained to swim through a rectangular pipe frame. The fish's ability to detect changes in the earth's magnetic field was measured by the number of passes through the pipe frame per minute. Correct responses were rewarded by a food reward delivered by an automatic dispenser; incorrect responses were punished by the food being withheld. The local vertical component of the earth's magnetic field was altered by passing an electrical current through a coil of wire encircling the tanks.

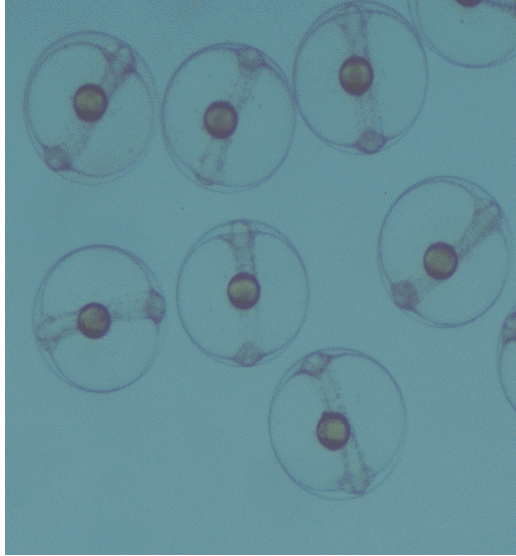
Olfaction -- Work conducted in the early years of the **Kewalo Research Facility** established that tunas have an excellent sense of smell that is capable of detecting the very dilute odor of their prey. Later research with captive tunas showed that they can distinguish between odors of different types of prey, and that some prey odors cause stronger search behavior than others, indicating that tunas probably use their sense of smell to detect prey before they come within visual range.

The later research on tuna olfaction was also aimed at analyzing the chemical structure of natural prey odors, developing synthetic prey odors, and testing the efficacy of these synthetic prey odors for eliciting a feeding response. Eventually, it may be possible to use natural and/or synthetic odors to enhance the effectiveness of traditional fishing techniques. If an inexpensive synthetic odor can be formulated, it could be used in the live-bait and the handline tuna fisheries to increase catch success and decrease dependency on expensive natural bait.

Spawning and rearing tunas and mahimahi (dolphin fish) -- The first successful attempts to artificially induce spawning in captive tuna were accomplished at the **Kewalo Research Facility**. The technique involved a periodic biopsy of kawakawa to determine the developmental stage of the eggs in the ovaries. After the eggs attained a critical size, hormone treatments were administered to induce spawning.

It was discovered that tuna eggs hatch about 24 hours after fertilization, and the yolk sacs of the larvae are absorbed in about 2 days. At this critical stage, the larval tuna must forage for food. To meet their nutritional requirements a culture system for species of phytoplankton, rotifers, and colepods was begun. The technology developed to rear larval tuna has opened new fields of research that focuses on the previously unobservable day-to-day development and early life history of pelagic fish.

Eventually, because of advances in techniques and knowledge, hormone treatments were no longer used and (during the summer months) skipjack tuna were routinely spawned at the **Kewalo Research Facility**. This enabled researchers to investigate many of the techniques needed to rear larval pelagic fish.



Skipjack tuna eggs (about 19 hours after fertilization) obtained from fish spawned at the **Kewalo Research Facility**. The eggs will hatch about 21 hours after fertilization. The dark spot visible in each egg is an oil globule that provides energy for the developing fish and ensures that the tiny eggs float. The actual diameter of the eggs is slightly less than 1 mm.

Building upon the experience gained with tunas, subsequent studies involved spawning and rearing mahimahi (dolphin fish or dorado, *Coryphaena hippurus*). Besides basic studies on the nutritional requirements, energetics and growth of mahimahi larvae, a series of studies on the tolerance to cold shock were also undertaken. These later experiments were designed to help assess the potential impacts of large-scale ocean thermal energy conversion projects, which move massive amounts of deep cold ocean water to the surface in a process (roughly analogous to a steam turbine) that generates electricity. Although this process produces no air pollutants, as does fossil fuel based electricity production, the potential biological impact of the cold water brought to the surface needed to be evaluated. Again, the **Kewalo Research Facility** with its unique combination of animal holding facilities and laboratories proved an ideal place to do the work.



These tiny mahimahi were reared from fertilized eggs. The lower individual is about 40 days old, the upper individual about 50 days old. When they first hatched, the fish were less than 1 mm long (less than the thickness of the dime pictured). Mahimahi reared in captivity will grow large enough to spawn within six months.

Burnt Tuna -- A major fishery in Hawaii is the handline fishery for large yellowfin and bigeye (*Thunnus obesus*) tunas. The fish landed are intended primarily for raw consumption as sashimi. The current value of the fishery is estimated at over \$5 million annually. There is also international interest in this type of fishing because of its low initial capital investment, low operating and fixed expenses, strong export markets, and high profitability. Unfortunately, the tuna handline (and primarily recreational troll fishery) are plagued by a product quality problem known as "burnt tuna", or in Japanese as "yake niku" (literally translated as "cooked meat"). When fish are intended for raw consumption, product quality is obviously of utmost importance!

For years, the high muscle temperatures and high muscle acidity created during the landing of large tunas on handlines were hypothesized to be the underlying cause of burnt tuna. However, when samples of burnt tuna muscle were examined at the histological and biochemical level, the observations did not fit the hypothesis. Based on the work of scientists at the **Kewalo Research Facility**, a new concept was developed, that burnt tuna is caused by activation of the proteolytic (protein destroying) enzyme known as "calcium activated neutral protease" or more commonly as "calpain". Efforts were directed at proving this hypothesis, development of a thorough understanding of the etiology of burnt tuna, and, more importantly, development strategies that could be used by fishermen to successfully mitigate this problem.

Surprisingly, it also learned that burnt tuna is not an isolated phenomenon, but rather that it is biochemically identical to processes occurring in heart muscle during heart attack and to some forms of human muscular dystrophy. Research that was begun to answer a specific fishery's product quality may someday prove to have medical importance!

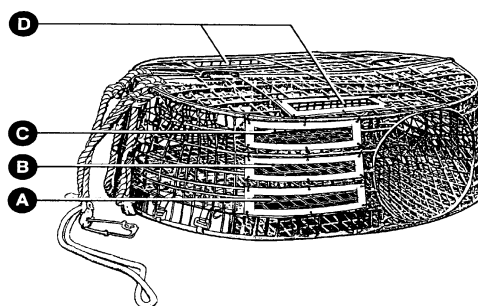
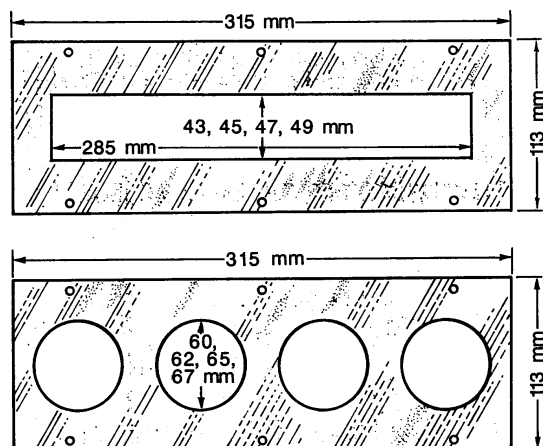
Lobsters & Deep Water Shrimp

Starting in the late 1970s the commercial fishery targeting spiny lobsters (*Panulirus marginatus*) and slipper lobsters (*Scyllarides spp.*) in the northwestern Hawaiian Islands experienced rapid expansion. Field research conducted by the Honolulu Laboratory showed that small (i.e., sublegal) lobsters brought up in traps were almost all eaten by fish,

before they reached the bottom, when thrown back. Escape gapes installed in commercial lobster traps were obviously need to prevent this problem and to retain a viable commercial fishery. But, how big should these escape gapes be?



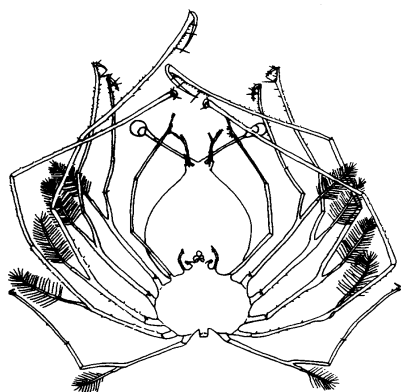
Hawaiian spiny lobsters held at the **Kewalo Research Facility** were used to test the optimal placement of escape vents that would retain legal sized animals yet let undersized individuals escape.



Fathoms Plus commercial lobster trap. The trap has been fitted with several escape vents and is used to determine the location which best allows the release of undersized lobsters. The vertical placement of escape vents are: A – 45 mm from the bottom; B – 115 mm from the bottom; C – 195 mm from the bottom; D – top of the trap.

Studies were begun at the **Kewalo Research Facility** were populations of known sizes of lobster were set up in the laboratory's shore side tanks. Lobster traps, with various size shapes of escape gapes, were added to the tanks and the size of lobsters retained carefully monitored. Optimal results were obtained using two escape gape panels with two circular openings 67 mm in diameter. Field trials conducted in the Northwestern Hawaiian Islands using similarly equipped traps, confirmed the efficacy of the system. As a result of this important laboratory and field research, all commercial lobster traps used in the Northwestern Hawaiian Islands must contain these exact escape vent panels.

Spawning and rearing -- Spawning and rearing studies at the **Kewalo Research Facility** centered on rearing of larval spiny and slipper lobsters and deep water shrimp (*Heterocarpus laevis*). Deep water shrimp, collected at sea, were successfully hatched and the larvae reared for up to 139 days in the laboratory, during which time they went through 37 molts! Similar techniques applied to slipper lobster larvae enabled them to be reared in captivity for up to 123 days. The objective of these studies were to provide important information useful for identifying the larval lobster and shrimp that often comprise a large part of specimens caught during plankton tows. These surprising long-lived larval stages also help explain how wide spread, apparently isolated adult populations can be genetically related. It is not the adults that migrate over long distances, but rather that their long lived planktonic larvae do. The fishery management implications of these discoveries are obvious.



The drawing of a lobster larva (phyllosome) hatched and reared at the **Kewalo Research Facility**. Little is known about the early life history of the commercially important lobster species caught near the Hawaiian Islands. Rearing lobster larvae in captivity from eggs allowed scientists to (1) identify the larval stages caught in plankton nets in the open ocean, (2) determine how long the larvae of various species remain in the plankton, and therefore (3) calculate how far the larvae could possibly be transported by oceanic currents.

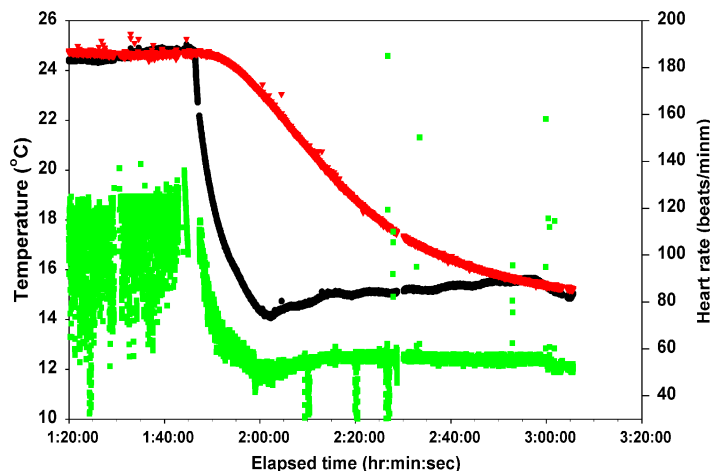
THE KEWALO RESEARCH FACILITY TODAY

Tunas

Laboratory experiments on the physiology and energetics of tunas -- Mathematical models of the energetics and physiological tolerances of tunas enable scientists to better explain and predict abundance and maximum sustainable yields. Much of the data collected over the past quarter century at the **Kewalo Research Facility** has been directed toward acquiring the data necessary for these models. Other models, integrating data from laboratory experiments on tunas with oceanographic information, indicated that the distribution of small tunas is most likely dependent on the availability of food whereas the distribution of larger fish is dependent on environmental conditions, of which temperature and oxygen levels play major roles.

Tuna biologists generally agree that temperature, ambient oxygen and prey abundance are the three principal factors determining the horizontal and vertical movements of tunas. These parameters not only dictate tuna habitat, but also influence the different tuna species' vulnerability to various types of fishing gear. The specifics of how these factors act and interact are, however, not well understood. It is the overall objective of the "Tuna Movements and Distribution" project (currently funded by the Pelagic Fisheries Research Program, Joint Institute for Marine and Atmospheric Research, University of Hawaii and centered at the **Kewalo Research Facility**) to employ state-of-the-art laboratory and telemetry studies to investigate the interactions between environmental conditions and tuna movements, distribution and vulnerability to capture. The studies on tuna physiology are thus aimed at providing a means of improving current tuna stock assessment methods.

In order to investigate further the physiological abilities and tolerances of tunas to temperature and oxygen conditions, a laboratory specifically designed to conduct physiological experiments on tunas has been developed at the **Kewalo Research Facility**. The laboratory contains a vibration-free operating table with running seawater and extensive physiological monitoring equipment. The temperature and oxygen levels of the water supplied to the operating table can be closely controlled and monitored. Tunas can be gently restrained on the table and have been found to respond normally when subjected to changes in environmental conditions.



Effects of an abrupt water temperature (red) change (25 to 15° C; 77 to 59° F) on heart rate (green) in yellowfin tuna. Heart rate follows changes in water temperature, not changes in muscle temperature (black), which lags significantly behind. These data show that yellowfin tuna at 15 °C (59 °F) do not have the ability to increase their heart rate (or cardiac output). Therefore the effect of temperature on the heart is a better explanation of how water temperatures limit the vertical movements of tunas than the effects of water temperature on muscle temperature.

Results of recent experiments using this system have shown that tunas are sensitive to even minute reductions of ambient oxygen that they will begin making physiological adjustments to reductions in ambient oxygen far smaller than those needed to elicit swimming speed changes. Data has also been obtained on the effects of rapid temperature change on tunas' metabolic rate and blood acid base chemistry, and the truly remarkable ability of tunas to recover from strenuous exercise.



Models of the function of tuna's cardio-respiratory systems ability to remove oxygen from the water passing over the gills have been recently developed based on data obtained in the physiology laboratory. Surprisingly, the results generated by these models imply that tuna's unique anatomy/physiology/biochemistry has evolved, not to permit high sustained cruising, but rather to permit rapid repayment of oxygen debts (i.e. rapid lactate metabolism).

A yellowfin tuna swimming the water tunnel designed and built by scientists from the Scripps Institution of Oceanography. This water tunnel was used to conduct advanced studies on the energetics, thermoregulatory and cardio-respiratory physiology, and biomechanics of swimming in tunas at the **Kewalo Research Facility**. A mirror above the fish allows investigators to view the tuna's swimming movements simultaneously from the side and top views.

Ultrasonic Tracking and Archival Tag Studies— The **Kewalo Research Facility** had at its disposal, the RV *Kahele' ale*. This 33-foot vessel was equipped with sophisticated electronics and navigational equipment to track the vertical and horizontal movements of tunas and billfishes carrying ultrasonic transmitters. The vessel was an integral part of the facility and was primarily used to test the results of theoretical and physiological investigations. The ability to hold tunas in captivity and to test various ultrasonic transmitter attachment methodologies on captive fish was critical to the success of the tracking studies. The project is now moving into its second phase, employing electronic data recording (i.e., archival) tags. These devices are capable of measuring and storing (for up to 12 years) data on ambient light levels, the fish's swimming depth and water temperature – data from which geographic positions can be calculated. The data collected in this research will be incorporated into more sophisticated computer models capable of predicting tunas' movements, distribution, and vulnerability to specific fishing gears.



The Honolulu Laboratory was one of the pioneers in the use of sonic tags to track tuna in the open ocean. The ability to test various methods for attaching ultrasonic transmitters to tunas using fish held at the **Kewalo Research Facility** was critical to the eventual success of this project. Here a yellowfin tuna outfitted with an ultrasonic depth-sensitive transmitter is about to be released back into the ocean.

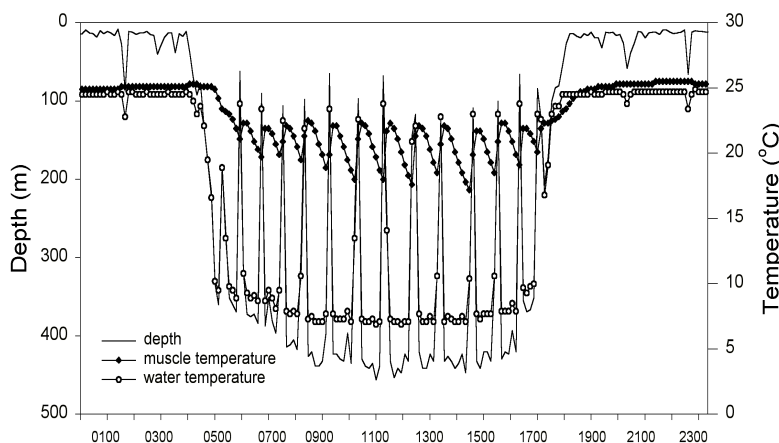


Data collected by tracking tunas with the RV *Kaahele'ale* is used to confirm results of experiments conducted at the **Kewalo Research Facility**. In addition to the normal fishing, navigational, and oceanographic equipment on board, a hydrophone is mounted at the bottom of the vertical pole located amidships. After a tuna is successfully tagged with an ultrasonic transmitter and released, the receiver is lowered into the water and the horizontal and vertical movements of the fish are then recorded. Results confirmed for the first time that tunas can be temporarily territorial and remain in a given area for some time in Hawaiian waters. Also of interest is the fact that tunas repeatedly return to the same area each morning, which implies that these fish can navigate and have a sense of time.

The larger yellowfin tuna is representative of the size of the fish held at the **Kewalo Research Facility** for approximately 10 months. The smaller fish is a newly capture yellowfin tuna and shows the size of the fish at the beginning of the study to determine optimal placement of new electronic data recording (archival tags). A portion of the simulated fiber optic light stalk from the model archival tag is seen protruding from the dorsal body musculature.



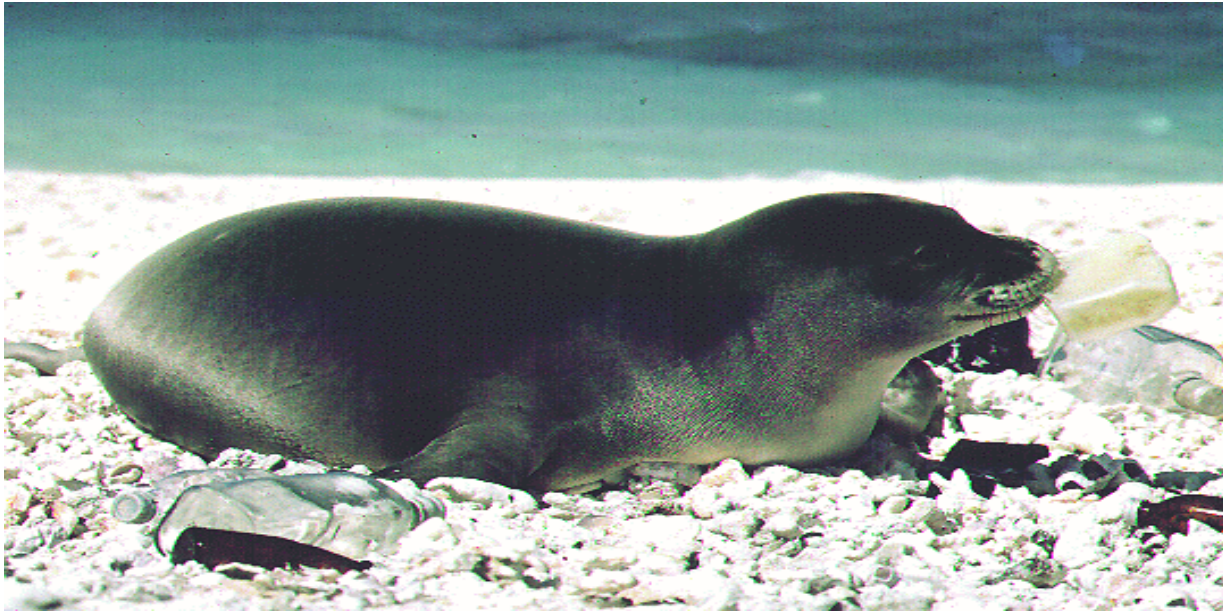
Although the engineering problems have been surmounted, long-term (months to years) attachments methods tag attachments methods remain problematic, especially for tunas and billfishes, where large individuals can be difficult to restrain or safely remove from the water. Again, the ability to test archival tag attachment techniques on tunas held at the **Kewalo Research Facility** is helping to keep these projects at the forefront of fisheries science.



Data from a recently recaptured bigeye tuna (*Thunnus obesus*) that had been at liberty for about 3 months after it was equipped with an archival tag. The record shows the fish's vertical movements, body temperature and water temperature over a representative 24-hour period. The archival tag was placed into the dorsal musculature after this surgical implantation technique was tested on captive fish held at the **Kewalo Research Facility**.

Hawaiian Monk Seals

The Hawaiian monk seal (*Monachus schauinslandi*), and the closely related species occurring in the Mediterranean, have remained virtually unchanged for 15 million years and are sometimes referred to as living fossils. The Caribbean monk seal became extinct in the mid-1950s; the Mediterranean population only has approximately 200-300 remaining individuals, and Hawaiian monk seal population numbers about 1,200-1,400 seals. Both Caribbean and Hawaiian monk seals are highly endangered animals.



Monk seal pup in the northwest Hawaiian Islands. Marine debris, including discarded fishing nets, in which seals become entangled, appear to pose a significant threat to recovery of this highly endangered species.

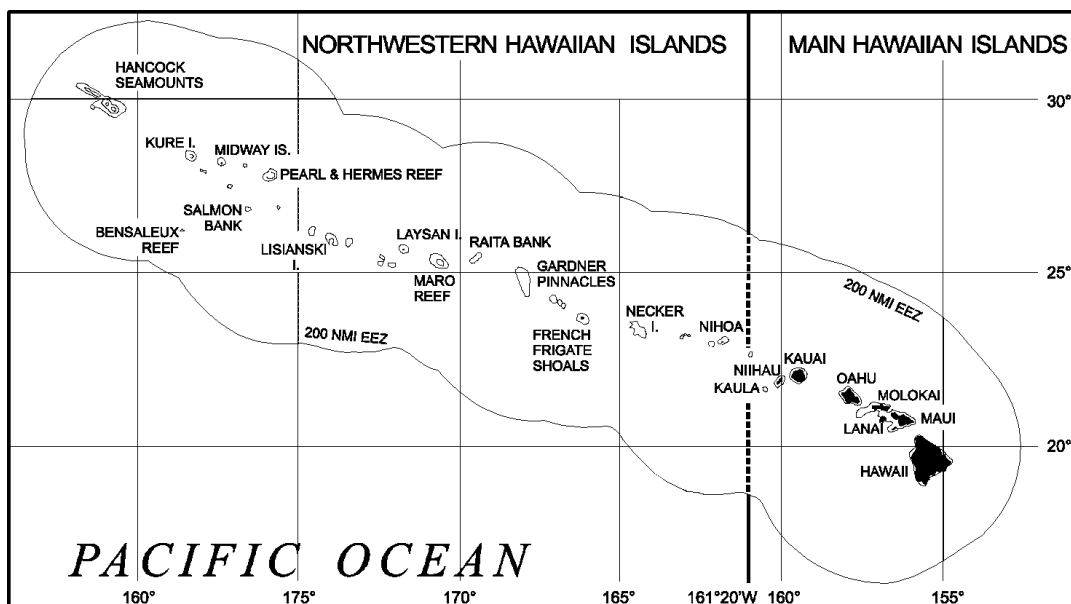
Hawaiian monk seals live near coral reef habitats and banks primarily in the Northwestern Hawaiian Islands (NWHI) where they forage and reproduce. Although, small numbers of seals are known to occur within the main Hawaiian Islands, the range of the species may have been restricted from the main Hawaiian Islands since the Polynesians first arrived in the islands. The seals' residence in the remote NWHI has not helped to conserve the species and its numbers have declined approximately 60% since the late 1950s. Hawaiian monk seals have been listed as an Endangered Species since 1976.

Natural and human factors have influenced Hawaiian monk seal population trends. Historical accounts indicate that Hawaiian monk seals were killed for food in the 1800s. During the mid 1900s, disturbance associated with military activities compromised monk seal use of preferred breeding locations and likely had a negative impact on population growth. Monk seals are the prey of sharks, and now limited prey resources at some locations plus adult male aggression due to a dysfunctional sex ratio threaten them even further. Entanglement in marine debris and ciguatera (i.e., fish) poisoning appear to be recent additional sources of mortality.

The primary objective of the National Marine Fisheries Service's Marine Mammal and Endangered Species Program is to enhance the recovery of the Hawaiian monk seal population. This goal is accomplished through regular population monitoring and studies of monk seal natural history, biology and ecology to identify and then, mitigate factors impeding population growth.

Monk seals, for the most part, lead a pelagic existence and spend approximately 70% of their lives at sea. They are also able to dive for food to depths greater than 500 m. Monk seals prefer to haul out on deserted beaches and atolls to rest, molt, pup and nurse their pups. Although docile, monk seals are extremely sensitive to any human disturbance and will leave preferred haul out areas. They will even desert their pups when disturbed. Since monk are frequently in danger from predation by sharks, more time spent in shark invested waters due to human disturbance means higher mortality rates. Displacement of seals to suboptimal haul-out habitat also increases their vulnerability to inclement weather and large waves generated from storms. Such conditions compromise survival, especially for naive pups and juveniles.

Each year field crews conduct censuses at the six main reproductive sites for the Hawaiian monk seal in the NWHI: French Frigate Shoals (FFS), Laysan Island, Lisianski Island, Pearl and Hermes Reef, Midway Atoll, and Kure Atoll. Field crews are sent out to these islands for one to six months at a time.



Since the late 1970s and early 1980s, biologists have been periodically assigned to these monk seal breeding locations to monitor population trends. In addition to counting seals they determine individual size, sex, identifying marks (tags), presence and approximate age of a pup, injuries and probable cause, and any pertinent natural history information. Field personnel also collect feeding habit information (fecal and vomit samples), remove entangling marine debris from the beaches, and disentangle all seals from such debris whenever possible.



Monk seals being held at the Kewalo Research Facility

Use of the **Kewalo Research Facility** is a key element in the success of the monk seal field research activities. All of the essential equipment used during the field camps is stored at the **Kewalo Research Facility**. Each year field biologists use the **Kewalo Research Facility** for staging research activities associated with

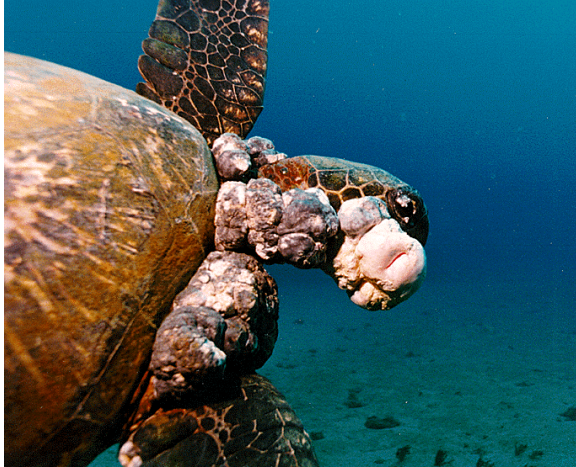
their long sojourns at these remote locations. In preparation for this work they carefully pack and inventory food, equipment, and supplies necessary for survival at each field camp. At the end of the field season all of the equipment is cleaned and stored to optimize potential use in subsequent years.

One project designed to enhance population growth has involved bringing sick or abandoned pups from the NWHI to the **Kewalo Research Facility** to be fed, weaned, and eventually returned to the wild to bolster population growth. This project has been so successful that some female seals, after spending more than a year in captivity and then being returned to the wild, have become successful breeding members of the population. The best example of the success of such rehabilitation and release efforts is at Kure Atoll, where population growth has been clearly enhanced due to these recovery efforts.

Research on captive monk seals has also been conducted at the **Kewalo Research Facility**. Studies have included testing techniques to lessen the aggressive behavior of adult male monk seals to reduce the problem of "mob mating". This phenomenon occurs at certain islands where the male to female sex ratio has become abnormally skewed over the years. Scientists using the **Kewalo Research Facility** have also investigated the metabolic rate of seals, which is important for determining the animal's energetic requirements and how much foraging habitat is necessary. This information is useful for developing appropriate fishery management regulations that best serve both fishermen and monk seals.

Hawaiian Sea Turtles

The **Kewalo Research Facility** provides an important laboratory where research on and resuscitation of the several threatened and endangered species of sea turtles found in the Pacific Ocean can be carried out. Successful recoveries of turtles either injured intentionally by spears or unintentionally by boat propeller have been achieved.



Sea turtle heavily afflicted with tumors. The problem is not limited to turtles around the main Hawaiian Islands, but is also unfortunately common on animals living in the western Atlantic, near the east coast of the United States.

The most common sea turtle around Hawaii is the green (*Chelonia mydas*, or *honu* in Hawaiian). These turtles are primarily vegetarian, eating algae growing on coral reefs. The smaller and rarer hawksbill turtle (*Eremochelys imbricata*, or *hono'ea* in Hawaiian) is found mainly around the islands of Molokai, Maui, and Hawaii. The large (up to 2,000 lb) leatherback turtle (*Dermochelys coriaca*) are rarely found close to the Hawaiian Islands, but are regularly seen in the open sea where they feed primarily on jellyfish.

Because of habitat destruction, direct exploitation of adults and eggs for food and other items, illegal poaching, ingestion of plastic debris, and unintended entanglement in fishing gear, sea turtle populations have been decimated world wide. But in Hawaii, another problem has recently cropped up, tumors! Research on this problem is continuing and involves turtles maintained at the **Kewalo Research Facility**, and cooperative efforts with scientists from governmental agencies and institutions both in Hawaii and on the mainland.

For more information about the National Marine Fisheries Service's involvement with Hawaiian monk seals and sea turtles, look on the web at: www.nmfs.hawaii.edu/psi/index.htm.

RELATIONSHIP WITH UNIVERSITY OF HAWAII and INSTITUTIONS OF HIGHER LEARNING AROUND THE WORLD

The **Kewalo Research Facility** maintains a special relationship with the University of Hawaii and other institutions of higher learning around the world. There is free dialogue and exchange of information among scientists in the University of Hawaii's Departments of Zoology, Physiology, Oceanography, Biochemistry, Nutrition, and Animal Sciences and researchers working at the **Kewalo Research Facility**. The National Marine Fisheries Service -- Honolulu Laboratory has provided part-time employment for University of Hawaii undergraduates and support for master's and doctoral degree candidates by providing laboratory space, access to experimental animals, and monetary grants. Laboratory scientists have also

served as advisors on graduate student thesis committees. These activities have provided enrichment to the mutual benefit of the University of Hawaii and the **Kewalo Research Facility**.

Graduate students from the who have earned advanced degrees that involved work at the **Kewalo Research Facility** have included:

University of Hawaii

Andrew Ayers	Department of Zoology
C. Scott Baker	Department of Zoology
Michael Barry	Department of Zoology
Gordon Bauer	Department of Psychology
Robert Bourke	Department of Animal Sciences
Richard Brill	Department of Physiology
Peter Bushnell	Department of Physiology
Ron Dunn	Department of Physiology
Sharon D. Hendrix	Department of Zoology
Walter N. Ikehara	Department of Zoology
Barbara A. Kuljis	Kewalo Basin Marine Animal Facility
Linda M. B. Paul	Department of Zoology
Anjanette S. Perry	Department of Oceanography
Elizabeth A. Monckton	Department of Zoology
Anthony Sudekum	Department of Zoology
Michael M. Walker	Department of Zoology
Cheryl Watson	Department of Physiology

University of British Columbia

Marvin Braun	Department of Zoology
Les Buck	Department of Zoology
Michael Guppy	Department of Zoology
Mark Heieis	Department of Zoology
Michael Herrick	Department of Zoology
Christopher Moyes	Department of Zoology
Tom Petersen	Department of Zoology
Manabu Shimazu	Department of Zoology
Jean-Michele Weber	Department of Zoology
Tim West	Department of Zoology

University of California, San Diego, Scripps Institution of Oceanography

Heidi Dewar	Physiological Research Laboratory
Peter Fields	Physiological Research Laboratory
Torre Knowler	Physiological Research Laboratory
Keith Korsmeyer	Physiological Research Laboratory
Nancy Aquilar	Physiological Research Laboratory
H. Scott Rapoport	Physiological Research Laboratory

University of Miami

Daniel Benetti Rosenteil

School of Marine and Atmospheric Science

University of Michigan

Chris Johnsrude

Department of Biology

Yonat Swimmer

Department of Zoology

University of St. Andrews

John Salamonski

Department of Physiology and Pharmacology

University of Wisconsin

Christofer Boggs

Laboratory of Limnology

Sherry Steffel

Laboratory of Limnology

Paul Johnsrude

Department of Biology

California State University, Fullerton

Janine Donley

Department of Biology

Chugi Sepulveda

Department of Biology

San Diego State University

Robert Olson

Department of Biology

Simon Fraser University

John Keen

Department of Biological Sciences

Holly Shiels

Department of Biological Science

Shizuoka Prefectural Fisheries Experimental Station

Minato Yasui

University of Aarhus

Christina Larsen

Department of Zoophysiology

LIST OF VISITING INVESTIGATORS

The **Kewalo Research Facility** is an international gathering place for scientists of varied backgrounds and disciplines. The uniqueness of this facility and the past years of quality research have engendered to it an enviable international reputation. Many respected scientists have taken the opportunity to study tunas and other marine species under the controlled laboratory conditions available only at the **Kewalo Research Facility**, a process which continues today. Scientists who have worked at the **Kewalo Research Facility** include:

Dr. Hiroki Abe	Laboratory of Chemistry, Kyoritsu Women's University
Dr. Alonso Aguirre	Colorado State University
Dr. Peter Arthur	Department of Zoology, University of British Columbia
Dr. Jelle Atema	Marine Biological Laboratory, Boston University
Dr. John E. Bardach	Resources Systems Institute, East-West Center
Dr. Grant R. Bartlett	Laboratory of Comparative Biochemistry
Dr. Robert Blake	Department of Zoology, University of British Columbia
Dr. Barbara Block	Department of Biology, University of Chicago
Dr. Peter Bushnell	Department of Biology, University of Indiana, South Bend
Dr. William P. Braker	John G. Shedd Aquarium
Dr. Ted Bullock	Department of Neurosciences, University of California, San Diego
Dr. Pat Butler	Department of Zoology and Comparative Physiology, University of Birmingham
Dr. Phyllis H. Cahn	Department of Biology, C. W. Post Center, Long Island University
Dr. Francis G. Carey	Woods Hole Oceanographic Institution
Dr. N. Chin Lai	Scripps Institution of Oceanography, University of California, San Diego
Dr. James W. Covell	Scripps Institution of Oceanography, University of California, San Diego
Dr. Jean L. Cramer	Department of Animal Sciences, University of Hawaii
Dr. Peter Davie	Department of Anatomy and Physiology, Massey University
Dr. Charles Daxboeck	Pacific Gamefish Foundation
Dr. Kathryn Dickson	Department of Biology, California State University, Fullerton
Dr. Brian Emmett	Department of Zoology, University of British Columbia
Dr. Anthony Farrell	Biological Sciences Department, Simon Fraser University
Dr. Craig Franklin	Department of Anatomy and Physiology, Massey University
Dr. Christopher French	Department of Zoology, University of British Columbia
Dr. F. E. J. Fry	Department of Zoology, University of Toronto
Dr. Alice Gibb	Department of Biology, California State University, Fullerton
Dr. F. W. Goetz, Jr.	Department of Biology, University of Notre Dame
Dr. Malcolm S. Gordon	Department of Biology, University of California
Dr. Jeffrey Graham	Scripps Institution of Oceanography, University of California, San Diego
Dr. E. Gordon Grau	Department of Zoology, University of Hawaii
Dr. Isao Hanyu	Laboratory of Fish Physiology, University of Tokyo
Dr. Teruo Harada	Fisheries Laboratory, Kinki University
Dr. Alan R. Hargens	Department of Surgery, University of California, San Diego
Dr. F. Havard-Duclois	Centre National pour l'Exploitation
Dr. Peter W. Hochachka	Department of Zoology, University of British Columbia
Dr. Kim Holland	Hawaii Institute of Marine Biology, University of Hawaii

Dr. C. S. Holling	Institute of Animal Resource Ecology, University of British Columbia
Dr. William C. Hulbert	Department of Zoology, University of British Columbia
Mr. Jeff Johansen	Department of Biological Sciences, Simon Fraser University
Dr. Ian Johnston	Department of Physiology and Pharmacology, University of St. Andrews
Dr. David Jones	Department of Zoology, University of British Columbia
Dr. John W. Kanwisher	Woods Hole Oceanographic Institution
Dr. Sergei M. Kashin	Institute of Oceanology, Academy of Sciences - Moscow
Mr. Haruyo Kashiwara	Cardiac Membrane Research Laboratory, Simon Fraser University
Dr. Steve Katz	Scripps Institution of Oceanography, University of California, San Diego
Dr. Calvin M. Kaya	Department of Zoology, Montana State University
Dr. Robert E. Kearney	South Pacific Commission
Dr. James F. Kitchell	Department of Limnology, University of Wisconsin
Dr. Keith Korsmeyer	Department of Biology, Hawaii Pacific University
Dr. John J. Magnuson	Department of Limnology, University of Wisconsin
Dr. Odile Mathieu-Costello	Department of Medicine, University of California, San Diego
Mr. Michael A. McCoy	Micronesian Maritime Authority
Dr. John M. Miller	Department of Zoology, University of North Carolina
Dr. William Milsom	Department of Zoology, University of British Columbia
Dr. Shigeru Miyashita	Fisheries Laboratory, Kinki University
Dr. Thomas W. Moon	Huntsman Marine Laboratory
Dr. Robert Morris	Makai Animal Clinic
Mr. Hank Marrow	Department of Anatomy, University of Hawaii
Mr. Barry S. Muir	Marine Ecology Laboratory, Bedford Institute of Oceanography
Dr. A. Earl Murchison	Naval Undersea Center
Dr. Claude M. Nagamine	Institute of Marine Resources, University of California
Dr. William H. Neill	Department of Wildlife and Fisheries Sciences, Texas A&M University
Dr. Arthur J. Niimi	Canada Center for Inland Waters
Dr. Hiroshi Niwa	Department of Fisheries, Nagoya University
Dr. Elmer R. Noble	Department of Biological Sciences, University of California, Santa Barbara
Dr. Kenneth R. Olson	South Bend Center for Medical Education, Indiana University
Dr. Steve Perry	Department of Biology, McMaster University Ontario, Canada
Dr. Douglas G. Pincock	Department of Electrical Engineering, University Brunswick
Dr. Warren P. Porter	Laboratory of Limnology, University of Wisconsin
Dr. John H. Prescott	Oceanarium, Inc.
Dr. Martin D. Rayner	Pacific Biomedical Research Center, University of Hawaii
Dr. Terence A. Rogers	Department of Physiology, University of Hawaii

Dr. Bryant T. Sather	Department of Zoology and Physiology, Rutgers University
Dr. Edward D. Scura	Aquatic Farms
Dr. Robert Shadwick	Scripps Institution of Oceanography, University of California, San Diego
Dr. Gary D. Sharp	Inter-American Tropical Tuna Commission
Dr. Terry Spraker	Colorado State University
Dr. John Steffensen	Marine Biological Laboratory, University of Copenhagen
Dr. E. Don Stevens	Department of Zoology, University of Hawaii
Dr. E. E. Suckling	Downstate Medical Center, State University of New York
Dr. J. A. Suckling	Department of Zoology, Hunter College of the City University of New York
Dr. Douglas Syme	Department of Biological Sciences, University of Calgary
Dr. Tamotsu Tamura	Agriculture Fisheries Laboratory, Nagoya University
Ms. Carina Taxboel	Marine Biological Laboratory, University of Copenhagen
Dr. Glen Tibbits	Cardiac Membrane Research Laboratory, Simon Fraser University
Dr. Vladimir Walters	Department of Zoology, University of California, Los Angeles
Dr. Clement Wardle	SOAEFD Marine Laboratory
Dr. Daniel Weihs	Department of Aeronautical Engineering, Israel Institute of Technology

PARTIAL LIST OF SCIENTIFIC PUBLICATION RESULTING FROM RESEARCH CONDUCTED AT THE KEWALO RESEARCH FACILITY

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Dr. John Magnuson (wearing a white shirt near the center of the photograph), an early pioneer in tuna research, and visitors inspecting a tank holding live tunas at the **Kewalo Research Facility** (circa 1965).

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